State-of-the-art Natural Gas Pipe Inspection

Venugopal K. Varma
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6304
varmavk@ornl.gov

Introduction: The safety of the Unites States' natural gas supply is of prime importance since 30% of the energy produced in the country is derived from it. Natural gas is supplied through a million miles of vast pipeline network [1]. Pipeline companies have an impressive safety record due to the proactive role of standards and inspection of pipelines. Since the pipelines are getting old, there is a great need to identify corrosion, cracks, and other defects that can cause potential problems.

There are two main ways of testing the integrity of pipelines. One is destructive inspection and the other is non-destructive testing. The destructive testing procedure uses hydrostatic inspection technique, to verify that a pipeline is within the safety margin for operation. The procedure does not however locate defects that are just above the threshold of the safety margin. In addition, the testing disrupts the pipeline's normal operation, for this reason it is not a preferred method. Generally, such techniques are good for offline inspection of pipelines before they are put into use. On the other hand, non-destructive inspection (NDI) techniques detect flaws that can cause potential failure in future. This way, NDI provides information on the integrity of the pipeline as well as a measure of its current safety margin.

This report will provide an overview of non-destructive testing approaches employed by the industry and a detailed synopsis of current research trends.

Flaw Detection: A pipeline that is in service can fail due to many causes. Some of the most common failure modes are Corrosion, Pitting, Stress Corrosion Cracks, Seam Weld Cracks, Dents, and other flaws due to external impact from earth-moving equipment. Ideally, it is prudent to detect all of the above cracks, but a technique used for detecting a particular flaw is not ideally suited to detect another. Hence, the gas industry uses a combination of techniques to ensure the safety margin for their operation. Probabilistic approaches have also been used for estimating pipeline integrity [2]. Probabilistic method attempts to predict safety using crack rate growth, inspection frequency, and operating parameters of the pipe. Researchers are also working on variations of different approaches (exploiting various phenomena of a particular technique) to extract more information on pipeline integrity. The goal of such research is to improve on the performance of the sensor without a complete redesign of the system.

Non-destructive Testing: The non-destructive testing of pipes can be broadly classified into magnetic flux leakage method and ultrasonic guided wave approach. These classifications can be further subdivided as follows:

- Magnetic Flux Leakage
  - Induction coil method

– Hall Effect Method

- Ultrasonic Method
  - Contact -→ Piezoelectric
    - ♦ Lamb Wave
    - ♦ Shear Wave

  - Non-Contact -→ EMAT , Magnetostrictive Sensor
    - ♦ Longitudinal Wave
    - ♦ Shear Wave

Magnetic Flux Leakage Method: The basic principle of the Magnetic Flux Leakage (MFL) method is that when a magnetic field is applied inside the pipe, the flux lines pass through the pipe wall. Although most of the flux lines pass through the pipe wall, few lines pass through the surrounding media (see Figure 1).

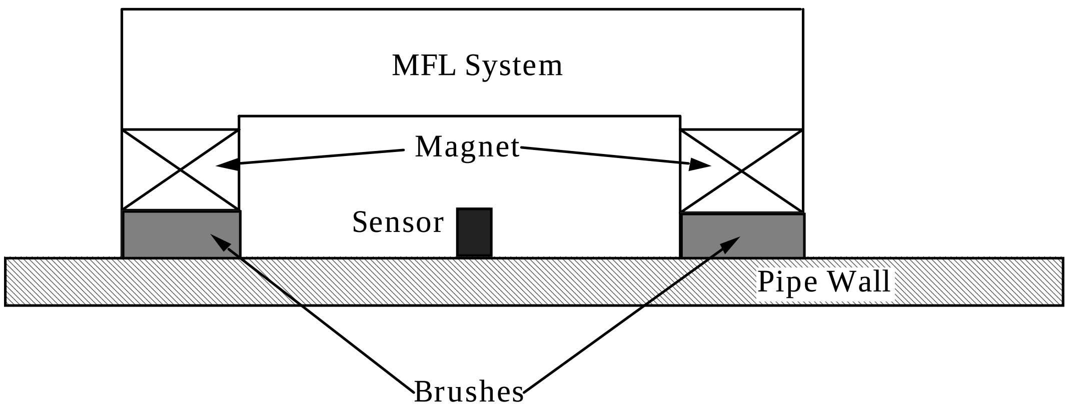

Figure 1. Schematic of MFL Sensor

When corrosion or other degradation of the wall occurs, the pipe wall thickness is reduced. Hence, at areas of corrosion (reduced wall thickness), the amount of magnetic flux carried is less than that with full wall thickness. This means that at these areas there is leakage of magnetic flux. The reduction in the wall thickness at both outer and inner walls of the pipe can cause the same effect [3].

A sensor placed inside the pipe near the area of reduced wall thickness senses increased flux density due to the MFL. The measured flux leakage is dependent on the material characteristics of the pipe, wall thickness, stresses in pipelines, and dimensions of the flaw. Apart from the reduction of wall thickness, a crack in the pipe wall can also cause flux leakage.

The MFL method, employs flux lines that are parallel to the axis of the pipe, is good for detecting corrosion, dents, or other anomalies, but MFL cannot detect axial stress corrosion cracks or seam weld cracks [4]. PII Group, U.K, has developed an MFL method using transverse magnetic field around the pipe rather in the axial direction to detect longitudinal cracks.

Research Areas in MFL: Using the same MFL technology, improvement in signal processing techniques has been used to characterize defects while rejecting signatures from pipeline features with no bearing on pipeline safety [5,6]. Surface size cracks in pipes can be estimated using Hall sensors measuring magnetic field leakage. Using the dipole model of cracks and no information about material parameters and boundary conditions, the crack size is estimated [7]. Using motion-induced remote field eddy currents, induced current at defect edges, and variable reluctance effect, MFL system's ability is enhanced to characterize defects [8]. There are motion-induced eddy currents that travel along the circumference of the pipes when an MFL instrument is passing through the pipe. Since the longitudinal cracks disrupt this eddy current formation, a measurement of the eddy current can yield the presence of longitudinal cracks [9]. The effectiveness of MFL corrosion characterization is dependent on knowing the material properties, stress, or loading pressure in pipelines. FEM modeling and laboratory experiments have been used to quantify the effect of biaxial stresses in MFL measurement [10]. Similar to MFL, Remote Field Electromagnetic Technique (RFET) is another method for detecting corrosion and pitting in pipes. Since the methodology does not use a permanent magnet, there is less probability of dust adhering to the probes used. Good correlation was obtained on 4" and 6" diameter pipes using the RFET method [11].

Ultrasonic Method: Other than magnetic field methods for detecting flaws, another method that has been extensively tested involves Ultrasonics. Ultrasonic waves traveling through the walls of the pipe will be affected by the features they encounter and can be measured to interpret the condition of the pipe. Most common ways of generating an ultrasonic wave is to use a piezoelectric device.

Piezoelectric devices need contact with the material to provide a good coupling to induce an ultrasonic wave. Generally, a liquid medium (e.g., oil, grease) is used to obtain this contact. In an instrument that is moving along the length of the pipe, getting a good contact has been difficult. Hence, most NDI measurements for pipe inspection have relied on MFL technology. The PII Group, U.K has circumvented this problem of good contact by employing a liquid-filled wheel contacting the walls of the pipe. The piezoelectric wave generator is situated inside the wheel, and the liquid provides a good coupling mechanism for its transmission and receiving. This methodology is employed in their Elastic wave vehicle design.

A newer method of ultrasonic testing that is gaining momentum is the EMAT (electromagnetic acoustic transducer) wave generator. The basic principle of EMAT is that a conductor carrying current near the surface of a metal under a magnetic field will induce an electromagnetic force given by Lorentz equation [12]. Also, if the material is ferromagnetic, a magnetostrictve effect takes place that can be five times more powerful than the Lorentz forces. This combination of forces acting on the material will generate Lamb, Shear, and Longitudinal ultrasonic waves in the material, depending on the configuration of the magnet and the direction of the current flow. Since the EMAT transducer does not touch the material being inspected, the main drawback of the piezoelectric ultrasonic is overcome with this approach. The signal an EMAT generates is not as strong as the ones obtained by other means and hence, extra care need to be employed in the signal processing and power conditioning circuits when using this approach (see Figure 2.).

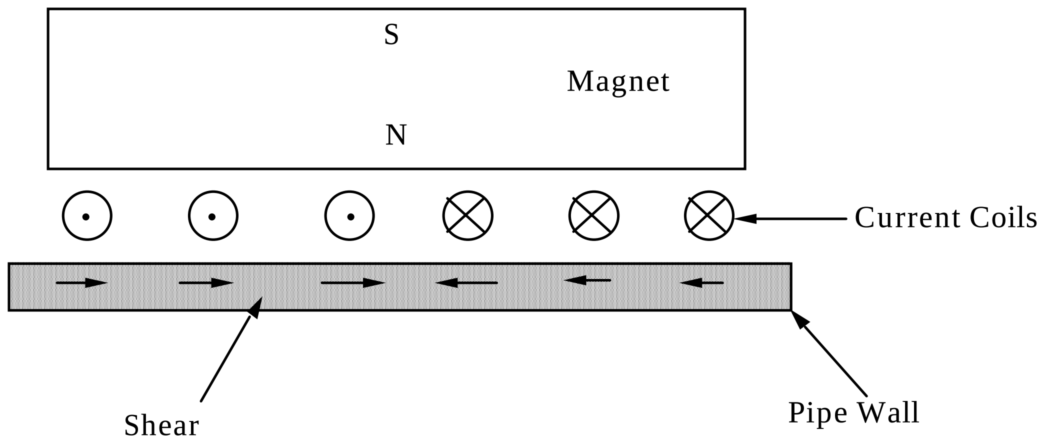

Figure 2. Schematic of an EMAT Transducer

Guided wave ultrasonic has been used for defect location in boiler tubes [13,14], bolt axial stress determination [15], and pipeline inspection [16,17,18]. Dispersion characteristics of ultrasonic waves are influenced by the operating frequency, wave-packet size, and the distance to the sensor [20]. Ideally, the dispersion of an acoustic wave needs to be minimized. Another characteristic that is of importance is the wave mode used for testing. Most researchers have either used the Sh_0 or the Sh_1in their experiments since by operating the EMAT at these frequencies, multiple mode generation could be avoided (higher operating frequencies will result in multiple modes being generated). There have been many recent developments in the manufacturing of the EMAT ultrasonic generator [18,20]. Sawaragi [20] talks about using an eight element probe instead of a four element probe, and Hamilton [18] discusses using a chirp signal to generate the input signal where ultrasonic wave sweeps linearly over a range of operating modes (due to change in frequency). Along the lines of the EMAT, Kwun [21,22] generated a longitudinal wave using magnetostrictive sensors. Apart from longitudinal and shear waves, Lamb waves produced with EMATs have also been used to study material defect and characterization [23,24,25].

Research direction: Ultrasonic guided waves have had successes in flaw detection, but it is still needs further study and validation before it can be accepted in the natural gas pipeline industry [18]. The proposed work is to develop a method using two orthogonal horizontal shear waves using EMAT to fully characterize the pipe flaws in a single pass. The objective of the project is to select the correct wave modes and sensor placement to fully capture the pipeline flaws. Modeling of the flaws, supplemented with experimental validation, will be used to better design the EMAT for maximum effectiveness.

References:

1. Posakony, G.J., and Hill, V.L., "Assuring the integrity of natural gas transmission pipelines," Topical Report, GRI, Nov. 1992.
2. Khaleel, M.A., and Simonen, F.A., "Effects of alternative inspection strategies on piping reliability," Nuclear Engineering and Design, Vol. 197, pp. 115-140, 2000.
3. Rosen, H., and Lewis, R., "Improved magnetic flux pipeline inspection tools in practice," pipeline pigging and inspection technology conference, Houston, TX, Feb. 17-20, 1992.
4. Porter, P.C., "Use of magnetic flux leakage (MFL) for the inspection of pipelines and storage tanks," Nondestructive evaluation of aging utilities, SPIE, Vol. 2454, pp. 172-184, 1995.
5. Udpa, L., Mandayam, S., Udpa, S., Sun, Y., and Lord, W., "Developments in gas pipeline inspection," Materials Evaluation, pp. 467-472, April, 1996.
6. Mandayam, S., Udpa, L., Udpa, S., and Lord, W., " Signal processing for inline inspection of gas transmission pipelines," Research in nondestructive evaluation, 8:233-247, Springer-Verlag, 1996.
7. Minkov, D., Takeda, Y., Shoji, T., and Lee, J., "Estimating the sizes of surface cracks based on hall element measurements of the leakage magnetic field and a dipole model of a crack," Applied Physics A, Materials Science & Processing, 2001.
8. Katragadda, G., Lord, W., Sun, Y.S., Udpa, S., Udpa, L., "Alternative magnetic flux leakage modalities for pipeline inspection," IEEE transactions on magnetics, Vol. 32, No: 3, May 1996.
9. Weischedel, H.R., "A novel electromagnetic method for the in-line inspection of gas pipelines: proof of concept experiments," GRI report, 96/0063, 1996.
10. Crouch, A.E., Beissner, R.E., Burkhardt, G.L., Creek, E.A., Grant, T.S., and Bruton, F.A., "Magnetic flux leakage inspection of gas pipelines: the effect of biaxial stress," GRI Report 95/0484, 1995.
11. Ramachandran, S., Kilgore, R.G., and McDougal, L.F., "Non-destructive examination of underground gas distribution lines using remote field electromagnetic technique (RFET)," Nondestructive evaluation of aging utilities, SPIE, Vol: 2454, 1995.
12. Thompson, R.B., "Physical Principles of Measurements with EMAT Transducers" Physical Acoustics, edited by W. P Mason, Academic Press, Vol. XIX, pp.157-199, 1990.
13. Gori, M., Giamboni, S., D'Alessio, E., Ghia, S., Cernuschi, F., and Piana, G.M., " Guided waves by EMAT transducers for rapid defect location on heat exchangers and boiler tubes," Ultrasonics, Vol. 34, pp. 311-314, 1996.
14. Gori, M., Giamboni, S., D'Alessio, E., Ghia, S., and Cernuschi, F., "EMAT transducers and thickness characterization on aged boiler tubes," Ultrasonics, Vol. 34 , pp 311-314, 1996.
15. Hirao, M., Ogi, H., and Yasui, H., "Contactless measurement of bolt axial stress using a shear wave electromagnetic acoustic transducer," NDT&E international, Vol. 34, pp. 179-183, 2001.
16. Hirao, M., and Ogi, H., "An SH-wave EMAT technique for gas pipeline inspection," NDT&E International, Vol. 32, pp 127-132, 1999.
17. Gauthler, J., Mustafa, V., Chabbaz, A., and Hay, D.R., "EMAT generation of horizontally polarized guided shear waves for ultrasonic inspection," International pipeline conference, Vol. 1, ASME, 1998.
18. Hamilton, J.C., "The development of an EMAT based in-line inspection system for the detection of stress corrosion cracks in operating pipelines," GRI report 00/0184, April, 2000.
19. Wilcox, P., Lowe, M., and Cawley, P., "The effect of dispersion on long range inspection using ultrasonic guided waves," NDT&E International, Vol. 34, pp 1-9, 2001.
20. Sawaragi, K., Salzburger, H.J., Hubschen, G., Enami, K., Kirihigashi, A., and Tachibana, N., "Improvement of SH-wave EMAT phased array inspection by new eight segment probes," Nuclear Engineering and Design, Vol. 198, pp. 153-163, 2000.
21. Kwun, H., Hanley, J.J., and Holt, A.E., "Detection of corrosion in pipe using magnetostrictive sensor technique," Nondestructive evaluation of aging maritime, SPIE, Vol. 2459, pp. 140-148, 1995.
22. Kwun, H., and Hanley, J.J, "NDE of steel Gas pipelines using magnetostrictive sensors," GRI report, 95/0362, October 1995.
23. Guo, Z., Achenbach, J.D., and Krishnaswamy, S., "EMAT generation and laser detection of single lamb wave modes," Ultrasonics, Vol. 35, pp. 423-429, 1997.
24. Murayama, R., " Study of driving mechanism on electromagnetic acoustic transducer for lamb wave using magnetostrictive effect and application in drawability evaluation of thin steel sheets," Ultrasonics, Vol. 37, pp. 31-38, 1999.
25. Castaings, M., and Hosten, B., " Lamb and SH waves generated and detected by air coupled ultrasonic transducers in composite material plates," NDT&E International, Vol. 34, pp. 249-258, 2001.